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AGRONOMY AND SOILS

Response of Cotton to P and K Soil Fertility Gradients in North Carolina

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ABSTRACT

Yield response of cotton to P and K soil fertility gradients in North Carolina was studied to augment the limited calibration data of the Mehlich-3 extractant procedure that is available. Sites were a Goldsboro fine loamy sand (1999, 2002), a Hiwassee clay loam (2002), and a Portsmouth fine sandy loam (1998, 1999). Linear-plateau and quadratic-plateau regression estimated critical soil and plant nutrient levels. Yield responded to fertility, but in some cases even fertilized plots remained below critical levels. The mean critical soil P level was 40 mg kg^{-1} on Portsmouth and 21 mg kg^{-1} on Goldsboro. There was no P response plateau on Hiwassee soil. In 2002, the critical soil K level was 64 mg kg^{-1} on Goldsboro and 137 mg kg^{-1} on Hiwassee soil. All plant tissue critical levels declined during the interval 1 wk prior to 5 wk after first bloom; critical leaf P declined from 3.1 g kg^{-1} to 2.0 g kg^{-1}, critical leaf K declined from 10.4 g kg^{-1} to 5.5 g kg^{-1}, and critical petiole K declined from 41.3 g kg^{-1} to 20.2 g kg^{-1}. The response data are within ranges of published critical levels, except P responses on the Portsmouth soil indicate a higher critical level than previously reported. Since Portsmouth and Goldsboro soils are likely to adsorb moderate amounts of P, and none of the soils are likely to adsorb K, fertilization at rates exceeding the P deficit (critical level minus actual concentration) by three-fold and equaling the K deficit should correct nutrient deficiencies.

Current P and K management recommendations for cotton (*Gossypium hirsutum* L.) in North Carolina are based on soil test levels (Tucker et al., 1997; Edmisten et al., 2004). Plant tissue analysis is also used to assess the nutrient status of a crop and provide recommendations either for the next crop or in-season fertilization of the current crop (Hodges, 1994; Mitchell and Baker, 2000; Crozier et al., 2002). Although P and K critical levels have been characterized for numerous grain crops (Cox and Lins, 1984; Heckman and Kamprath, 1992; Cox, 1996), tobacco (*Nicotiana tabacum* L.) (Denton et al., 1987), and Irish potato (*Solanum tuberosum* L.) (McCollum, 1978) in North Carolina, limited data are available for cotton.

Numerous studies have described the yield response of cotton to P and K fertilization (Long and Seatz, 1953; Bennet et al., 1965; Mullins et al., 1999; Adeli and Varco, 2002), but only a few permit characterization of critical soil or plant tissue nutrient levels.

Other studies have described critical soil test levels for cotton (Bingham, 1966; Ulrich and Ohki, 1966; Mitchell and Baker, 2000). Little of this work is based on the Mehlich-3 extractant, which is currently the basis of North Carolina soil test recommendations (Mehlich, 1984; Tucker et al., 1997). The Mehlich-3 extractant was developed and adopted for routine use by the North Carolina Department of Agriculture, Agronomic Division Laboratory, because it improved correlations between soil test P and crop yield over the Mehlich-1 extractant (0.05 N HCl + 0.05 N H_2SO_4), and was also effective in quantifying soil K, Ca, Mg, Na, Cu, Mn, and Zn (Mehlich, 1984).

Previously published critical levels of soil P and K range widely depending upon soil type, extractant used, and sample timing. Published critical levels of soil P include 6 to 12 mg kg^{-1} with a Mehlich-1 extractant (Bingham, 1966; Cope, 1984), 12 mg kg^{-1} with a Mehlich-3 extractant (Cox and Barnes, 2002), and 14 to 32 mg kg^{-1} with a bicarbonate extractant (Duggan et al., 2003). Critical soil K levels range from 40 to 141 mg kg^{-1} with a Mehlich-1 extractant (Ulrich and Ohki, 1966; Cope, 1984; Baker et al., 1994; Davis et al., 1996; Howard et al., 2001; Adeli and Varco, 2002), and 39 to 130 mg kg^{-1} with a Mehlich-3 extractant (Davis et al., 1996; Weir et al., 1996; Cox and Barnes, 2002).

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Studies of critical levels in plant tissue have been summarized in Bingham (1966), Ulrich and Ohki (1966), Sabbe and Zelinski (1990), and Mitchell and Baker (2000). In the literature, critical levels are less variable in cotton tissue than in soil. Concentrations of critical nutrients in plant tissue decline during the flowering period. Critical P levels in the leaf decline from 2.0 g kg^{-1} at early bloom to 1.5 g kg^{-1} at late bloom/maturity (Mitchell and Baker, 2000), or from 2.8 g kg^{-1} at first square to 2.0 g kg^{-1} at flowering (Bingham, 1966). Similarly, critical leaf K levels decline from 10 to 15 g kg^{-1} at floral initiation to 9.0 to 7.5 g kg^{-1} by late bloom (Cope, 1984; Mitchell and Baker, 2000; Howard et al., 2001; Cox and Barnes, 2002). Critical K levels in the petioles also declined from 37 to 45 g kg^{-1} to 10 to 15 g kg^{-1} during the same reproductive intervals (Ulrich and Ohki, 1966; Mitchell and Baker, 2000).

Due to past fertilizer applications, it is difficult to identify suitable experimental sites with P and/or K deficient soils. Field studies in North Carolina have failed to detect yield response to soil- or foliar-applied K fertilizer at sites with initial soil test K concentrations greater than 130 mg kg^{-1} (Crozier et al., 2002; Nixon et al., 2002). A recent North Carolina study used a single long-term soil fertility site and identified a critical level of soil K in 1 of 3 yr (Cox and Barnes, 2002). Critical levels of soil P were also reported for this site. Since response of corn (*Zea mays* L.) to soil P gradients depends on clay content in the soil (Cox and Lins, 1984; Cox, 1994a), additional studies on different soil types are warranted. The objectives of this manuscript are to characterize responses of cotton to P soil fertility gradients at 3 sites and K soil fertility gradients at 2 sites, and to compare responses with critical levels for soil and plant tissue predicted in published research.

MATERIALS AND METHODS

The experiments were conducted in North Carolina on three long-term soil fertility sites (Tables 1 and 2). Soils were a Goldsboro sandy loam (fine-loamy, siliceous, subactive, thermic, Aquic Paleudults) at the Peanut Belt Research Station near Lewiston (1999, 2002), a Hiwassee clay loam (fine, kaolinitic, thermic, Rhodic Kanhapludults) at the Piedmont Research Station near Salisbury (2002), and a Portsmouth fine sandy loam (fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults) at the Tidewater Research Station near Plymouth (1998, 1999). Fertilizer treatments have been applied to designated areas since each site was established (Table 1). The Peanut Belt site is the same one used by Cox and Barnes (2002), but K application rates were increased to 93 kg ha^{-1} to enhance the likelihood of attaining yield plateau levels. Soil test P treatments are present at all sites, but K treatments are only present at the Peanut Belt and Piedmont sites. Prior to the current study, fields were managed for several years in a corn/wheat [*Triticum aestivum* (L.) em. Thell.]/soybean [*Glycine max* (L.) Merr.] rotation at the Tidewater and Piedmont sites, and a corn/peanut (*Arachis hypogaea* L.)/cotton rotation at the Peanut Belt site.

Table 1. Field sites, characteristics, and rates of P and K fertilizer applied to attain fertility gradients

Site	Soil series	Date established	Plot dimensions (m)	Reps (#)	P (kg ha^{-1})	K (kg ha^{-1})
Peanut	Goldsboro	1982	7.3 x 15.2	4	0, 10, 20, 39	0, 47, 93
Piedmont	Hiwassee	1985	5.8 x 13.7	4	0, 10, 20, 39	0, 19, 37, 75
Tidewater	Portsmouth	1966	6.4 x 52.9	6	0, 10, 20, 39, 59	- - -

Table 2. Soil fertility characteristics of each study site

Site	Humic matter [g $(100cm^3)^{-1}$]	Weight/volume (g cm^{-3})	pH	CEC [meq $(100\ cm^3)^{-1}$]	Ca [meq $(100\ cm^3)^{-1}$]	Mg [meq $(100\ cm^3)^{-1}$]	K [z] [meq $(100\ cm^3)^{-1}$]		P [z] (mg kg^{-1})	
							None	Max.	None	Max.
Peanut	0.75	1.27	5.8	6.05	3.86	0.79	30	103	7.8	57.2
Piedmont	0.15	1.17	5.9	6.45	3.24	1.60	82	164	1.1	9.2
Tidewater	3.00	1.19	6.1	8.31	5.00	1.78	- - -	138	18.4	56.2

[z] Means are provided for all plots receiving no P or K fertilizer for the most recent sampling date (none) and for all plots receiving the maximum P or K fertilizer rate for the most recent sampling date (max.).

All field tests were conducted using a randomized complete block design. Gradients of P and K fertility were generated by pre-plant broadcast application of triple superphosphate (0-46-0) or muriate of potash (0-0-60). Standard agronomic management practices were followed, including applications of lime, N, and micronutrient fertilizer (Tucker et al., 1997; Edmisten et al., 2003). Total N rates (at planting plus sidedress) ranged from 64 to 112 kg ha^{-1}, depending on the site and the prior rotational crop. At the Tidewater site, 'DeltaPine 425' (Delta Pine and Land; Scott, MS) was planted in 1998 and 'Stoneville BXN 47' (Stoneville Pedigreed Seed; Memphis, TN) was planted in 1999, both at 136,000 seeds ha^{-1} with 91-cm row spacing following conventional tillage. At the Peanut Belt site, 'Suregrow 125' (Delta Pine and Land; Scott, MS) was planted in 1999 and 'DeltaPine 451' (Delta Pine and Land; Scott, MS) was planted in 2002, both at 143,000 seeds ha^{-1} with 91-cm row spacing following conventional tillage. At the Piedmont site, DeltaPine 451 was planted no-till at 172,000 seeds ha^{-1} with 76-cm row spacing.

Prior management at all sites included withholding P and K fertilizers on selected years to permit the monitoring of changes in soil-test levels (Cox et al., 1981). At the Tidewater site, main plots were split into four subplots each receiving different initial P fertilizer rates in 1966 (Cox et al., 1981). In 1998, subplots were sampled separately that resulted in 120 yield, soil, and plant tissue values. Based on lack of subplot treatment effects in 1998, main plots were sampled in 1999 (30 yield, soil, and plant tissue values). The Piedmont site had been abandoned for research, and managed with uniform K and no P fertilizer applications for several years prior to this study. At the Peanut Belt site, soil-applied K rates were lower (0, 42, and 84 kg ha^{-1} in 1993 and 1996, and 0, 31, and 62 kg ha^{-1} in 1991) on cotton prior to the current study.

Soil samples (0 to 20-cm depth) were collected at first bloom from all sites each year and analyzed by the North Carolina Department of Agriculture & Consumer Services (NCDA&CS) Agronomic Division Laboratory using Mehlich-3 extractant (Tucker, 1992a; Tucker, 1992b; Tucker et al., 1997). Samples were collected mid-season, rather than pre-season, in order to document the soil nutrient concentration resulting from the fertilizer application. This avoided the need to predict available P levels, which vary based on clay content of the soil (Cox, 1994b), or to collect multiple samples to monitor changing P and K levels associated with fertilizer dissolution, crop uptake, and leaching (James and Wells, 1990).

Leaves and petioles from the youngest fully expanded leaf were collected 1 wk after first bloom at the Tidewater site and on multiple dates at the other sites. Tissue samples were collected 1, 3, and 5 wk after first bloom at the Peanut Belt site in 1999. Tissue samples were collected 1 wk prior to first bloom and 1, 3, and 5 wk after first bloom at the Peanut Belt and Piedmont sites in 2002. Leaf blades (hereafter called leaf) were analyzed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and B; and petioles were analyzed for nitrate and K using standard methods of the NCDA&CS Agronomic Division Laboratory. When the small size of some petioles precluded analysis for some individual plots, petiole results were omitted for the entire experiment on these dates. Analytical results for nutrients other than P and K are not presented, but nutrient limitations besides P or K were not identified at these sites.

Plots were irrigated at the Peanut Belt and Piedmont sites, but a limited supply of water resulted in some drought stress at the Piedmont site in 2002. Yields were also reduced by hurricane damage at the Tidewater and Peanut Belt sites in 1999. Yield data were obtained by either machine-harvest of two, 15-m row segments (Peanut Belt), or hand-harvest of 6.1 m of row (Piedmont and Tidewater).

Statistical analyses of P data used linear-plateau regression of soil or plant tissue P concentration on seed cotton yield with the NLIN procedure available in SAS (version 6, SAS Institute Inc.; Cary, NC). Initial parameter estimates were derived separately for each site-year by plotting yield response to nutrient level with the REG procedure and "plot" option available in SAS. The lower limit of the plateau portion of the function was considered to be the critical level (Cate and Nelson, 1971), and the mean was calculated across site-years for comparison with published critical levels. If there was no projected critical level within the range of our data, linear regression alone (SAS REG procedure) was used to define the response relationship without specifying a critical level. Since fertility levels for K were often not high enough to result in a clearly defined response plateau, a quadratic-plateau regression model was used. The critical level for K response was the value associated with a yield level of 95% of the projected yield plateau, which was calculated using the quadratic formula. If this estimated critical level was beyond the range of our data, linear regres-

sion alone was used as described for P response. All regression models were statistically evaluated using the regression test (Steel and Torrie, 1980).

Regression analysis was used since fertilizer treatments resulted in a continuum of nutrient availability rather than step-wise increments. Crop responses to nutrient levels can also be characterized using analysis of variance or exponential functions. Nevertheless, the linear-plateau method provides a simple quantification of the critical level that is independent of fertilizer and cotton price fluctuations (Cate and Nelson, 1971; Dahnke and Olson, 1990; Cox, 1996). Similarly, selection of the 95% of maximum yield level has been used to estimate critical level based on the quadratic-plateau model (Tisdale et al., 1993).

RESULTS AND DISCUSSION

Fertilizer treatments resulted in gradients of soil and leaf tissue concentrations, and in yield responses that frequently attained plateau levels. Although lint turnout and fiber quality were not evaluated in our study, previous studies indicate differences are possible but not always substantial (Bennett et al., 1965; Cassman et al., 1989; Pettigrew et al., 1996; Gormus and Yucel, 2002; Bauer et al., 1998). Differences in fiber quality, such as a reduction in 50% span length from 1.37 cm to 1.35 cm and a reduction in micronaire from 4.1 to 3.7 associated with K deficiency (Pettigrew et al., 1996), while statistically significant, represent relatively minor differences considering the 0.08 cm difference between staple length categories and the optimal micronaire range of 3.5 to 4.9 (Perkins et al., 1984). Existing data suggest that two- to three-fold differences in crop yields, such as those observed in our study, will have a larger effect on production economics than subtle differences in quality parameters.

Seed cotton yield levels at our sites ranged from 1.0 to 3.6 Mg ha^{-1} in comparison to North Carolina statewide average cotton yields of 1.9 Mg ha^{-1} from1998 to 2002 (Murphy and Hayes 1999; 2001; 2003). Realistic yield expectations that have been published for these soils are 2.70 Mg ha^{-1} for Goldsboro (Peanut Belt), 1.84 Mg ha^{-1} for Hiwassee (Piedmont), and 2.42 Mg ha^{-1} for Portsmouth (Tidewater). Crop yields were lower than typical levels in 1999 due to hurricane-related flooding prior to harvest, and in 2002 at the Piedmont site probably because of the combined effects of drought and prior erosion.

Although this study did not directly evaluate the rate of P or K fertilizer required to correct deficiencies, we can hypothesize regarding fertilization rates based on general assumptions of the strong bonding of P and lack of bonding of K to soil adsorption sites (Corey, 1990), and on specific estimates that two-thirds of applied fertilizer P will be adsorbed by Portsmouth (Cox et al., 1981), and presumably by Goldsboro soils. Based on these assumptions, P fertilizer should be applied at rates exceeding P deficits (critical P level minus actual P level) by a factor of three, while K fertilizer should be applied at rates equaling K deficits. Standard fertilizer recommendations by the NCDA&CS laboratory based on soil test nutrient levels use the following equations (Tucker et al., 1997), which yield lower P recommendations and higher K recommendations than those based on our hypotheses.

The equation for P fertilization is

$$\text{kg P ha}^{-1} = 0.004754\ (ab)^2 - 1.565\ (ab) + 73.4$$

where a = soil test P (mg kg^{-1}) and b = soil weight: volume ratio (g cm^{-3}).

The equation for K fertilization is

$$\text{kg K ha}^{-1} = 0.00293\ (ab)^2 - 1.385\ (ab) + 154$$

where a = soil test K (mg kg^{-1}) and b = soil weight: volume ratio (g cm^{-3}).

Soil P gradient response. Yield responses to the soil P gradient were observed for all 5 site-years and response plateaus were identifiable for 4 of the 5 site-years (Fig. 1-5). The mean critical level of soil P at first-bloom was 40 mg kg^{-1} at the Tidewater site and 21 mg kg^{-1} at the Peanut site. There was no yield plateau in response to the soil P gradient at the Piedmont site (Fig. 5). A model proposed by Cox and Lins (1984) indicates mid-season critical levels for corn range from 12 to 25 mg kg^{-1} for soils with 200 to 400 g kg^{-1} clay. Although particle size was not quantified, the Hiwassee soil at the Piedmont site is an eroded ultisol with a clayey surface layer, so soil P levels were probably insufficient even at the highest fertilizer rate. In addition, variability due to slope and uneven erosion may have contributed to the lack of a clear P response plateau relationship.

Leaf P gradient response. As with soil gradients, yield increased as the concentration of P in leaves increased at all sites (Fig. 1-5, Table 3). Response plateaus were identified for 7 of the 13 models based on all sites and tissue sampling stages (Table 3). Response plateaus were not observed for the Piedmont site at any tissue sampling stage.

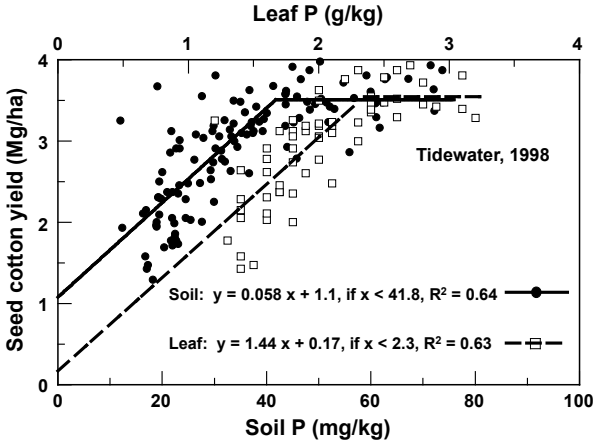

Figure 1. Yield response of cotton to soil and plant P levels at the Tidewater Research Station in 1998. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

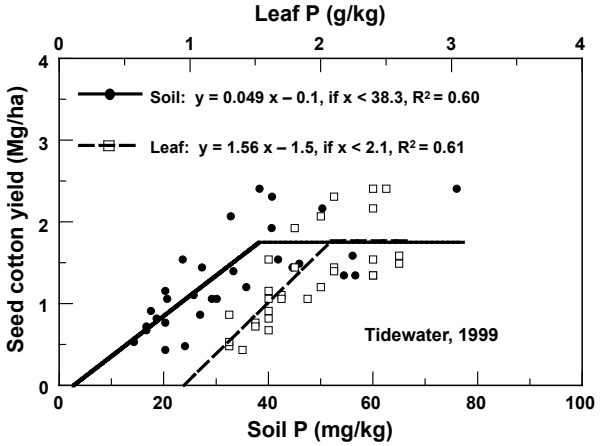

Figure 2. Yield response of cotton to soil and plant P levels at the Tidewater Research Station in 1999. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

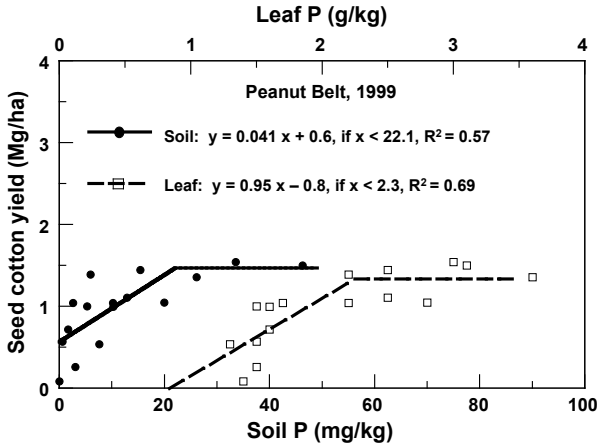

Figure 3. Yield response of cotton to soil and plant P levels at the Peanut Belt Research Station in 1999. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

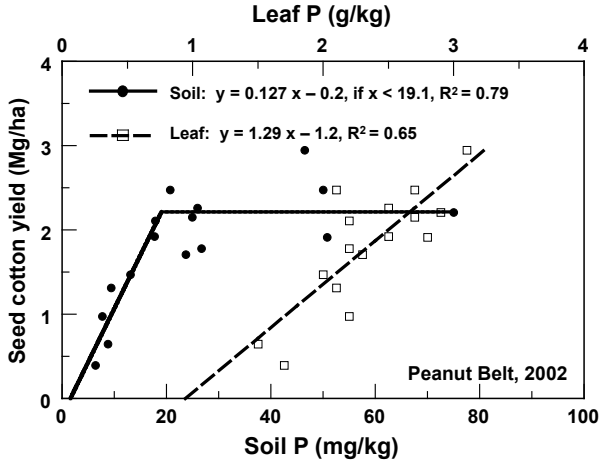

Figure 4. Yield response of cotton to soil and plant P levels at the Peanut Belt Research Station in 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

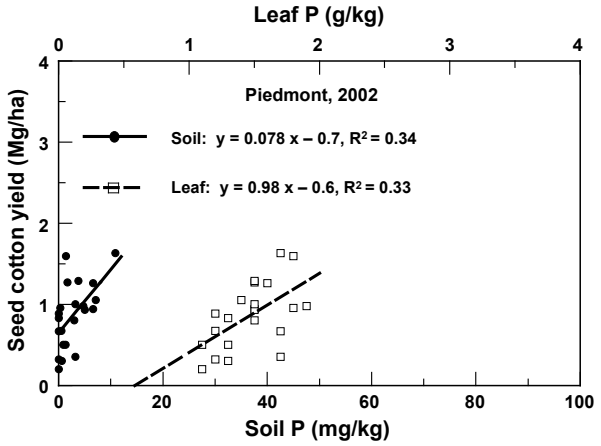

Figure 5. Yield response of cotton to soil and plant P levels at the Piedmont Research Station, 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

Critical P levels. Our estimates of critical P levels are compared with published levels in Table 4. At the Peanut site, critical soil P level was higher than the value of 12 mg kg^{-1} (calculated from 16 mg L^{-1} and estimated soil density) reported by Cox and Barnes (2002). Cotton yields during the Cox and Barnes (2002) study may have been K-limited, so the crop was unable to respond to P increases. Studies using different extractants found pre-season critical levels ranging from 6 to 12 mg kg^{-1} for different soils using the Mehlich-1 extractant (Bingham, 1966; Cope, 1984), 22 mg kg^{-1} for a Georgia Piedmont site using 0.5N HCl extractant (Stelly and Morris, 1953), and between 14 and 32 mg kg^{-1} for a site in tropical

Table 3. Values of linear-plateau regression model parameters indicating seed cotton yield (y) in response to leaf P gradients (x), and yield plateau (y_o) at the critical level (x_o) based on the equation, $y = a + bx$, if $x < x_o$.

Sampling stage [y]	Site	Year	a (Mg ha^{-1})	b [(Mg ha^{-1})(g kg^{-1})$^{-1}$]	x_o (g kg^{-1})	y_o (Mg ha^{-1})	R^2
-1	Peanut	2002	-1.90	1.33	3.10	2.22	0.76** [z]
	Piedmont	2002	-0.03	0.333	- - -	- - -	0.20*
+1	Tidewater	1998	0.17	1.44	2.35	3.55	0.63**
	Tidewater	1999	-1.49	1.56	2.08	1.77	0.61**
	Peanut	1999	-0.80	0.948	2.25	1.33	0.69**
	Peanut	2002	-1.22	1.29	- - -	- - -	0.65**
	Piedmont	2002	-0.57	0.976	- - -	- - -	0.33**
+3	Peanut	1999	-0.67	0.803	2.54	1.38	0.85**
	Peanut	2002	-0.07	0.514	- - -	- - -	0.48**
	Piedmont	2002	-0.56	1.01	- - -	- - -	0.57**
+5	Peanut	1999	-0.64	1.15	1.81	1.45	0.67**
	Peanut	2002	-2.99	2.48	2.23	2.54	0.74**
	Piedmont	2002	-0.46	1.06	- - -	- - -	0.37**

[y] Sampling stage is relative to first bloom (0).

[z] Values designated with * and ** are significantly different at $P \leq 0.05$ and 0.01, respectively.

Table 4. Critical soil and plant tissue P levels from this study and selected publications

Parameter		This study [x]		Reference [y]	
Critical level of soil P	n	(mg kg^{-1})	CV (%)		(mg kg^{-1})
				Stelly & Morris (1953)	22
				Bingham (1966)	Clays: 6 to 7
	2	Tidewater: 40.0	6.2		Sands: 8 to 12
	2	Peanut: 20.6	10.4	Cope (1984)	7
				Cox & Barnes (2002)	12
				Duggan et al. (2003)	14 to 32
Critical level of leaf P [z]		(g kg^{-1})	(%)		(g kg^{-1})
1st square		---		Bingham (1966)	2.8
-1 wk	1	3.10	- - -		
+1 wk	3	2.23	6.1	Cope (1984)	3.0
				Mitchell & Bake (2000)	2.0
+3 wk	1	2.54	- - -	Bingham (1966)	2.0
				Cox & Barnes (2002)	2.1
+5 wk	2	2.02	14.7	Mitchell & Baker (2000)	1.5

[x] Critical level of soil P in this study was determined using the Mehlich-3 extractant.

[y] Critical levels of soil P for Stelly and Morris, Bingham, Cope, Cox and Barnes, and Duggan et al. were determined by 0.5 N HCl, Mehlich-1, Mehlich-1, Mechlich-1, Mehlich-3, and bicarbonate extractants, respectively. Critical level of leaf P were determined by Cope, Mitchell and Baker (at +1 wk), Bingham, and Mitchell and Baker (at +5 wk) at early bloom, early bloom, flowering, and late bloom/maturity, respectively.

[z] Sampling stages are relative to first bloom (0).

Australia using the bicarbonate extractant (Duggan et al., 2003). Tidewater region soils in this study had a higher level of critical soil P (40 mg kg^{-1}) than has been reported previously, but results from our sites are similar to predictions for corn by Cox and Lins (1984). Their model indicates critical Mehlich-3 P levels of 25 to 50 mg kg^{-1} for corn grown on soils with 100 to 200 g kg^{-1} clay, which is the approximate topsoil clay content for the Tidewater and Peanut Belt soils.

Mean critical tissue P levels declined during the bloom period, which is in agreement with previous studies. Critical leaf P level declined from 3.1 g kg^{-1} for the week prior to first bloom to 2.0 g kg^{-1} for 5 wk after first bloom (Table 4). A similar trend, with different concentrations, was reported by Bingham (1966) and Mitchell and Baker (2000).

Soil K gradient response. Yield increases in response to the soil K gradient were observed for all 3 site-years and critical levels were detected at both sites in 2002 (Fig. 6-8). Cox and Barnes (2002) observed a critical soil test K level in 1 of 3 yr at the same Peanut Belt site that indicate actual soil K concentrations achieved as a result of their fertilizer treatments remained deficient. Annual fertilizer application rates were increased for this study, and by 2002 maximum soil test K levels had approximately doubled those reported by Cox and Barnes (2002). Even with these increased K fertilization and soil test levels, there were few data points in the plateau region of this relationship (Fig. 7). Attainment of even higher levels of soil test K would improve confidence in our estimate of critical levels. Nevertheless, data from other North Carolina field sites have failed to detect yield response to soil- or foliar-applied K fertilizer at sites with initial soil test K concentrations greater than 130 mg kg^{-1} (Crozier et al., 2002; Nixon et al., 2002).

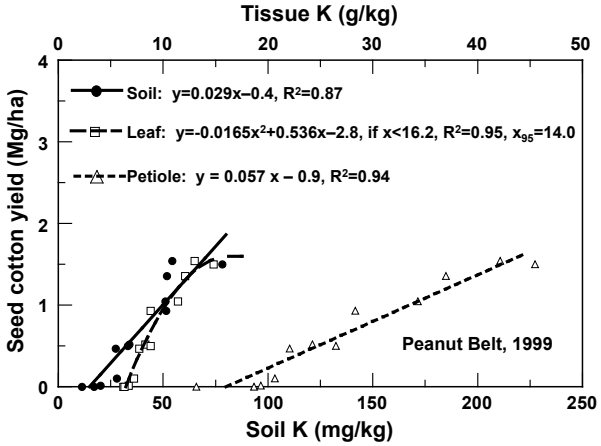

Figure 6. Yield response of cotton to soil and leaf K levels at the Peanut Belt Research Station in 1999. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

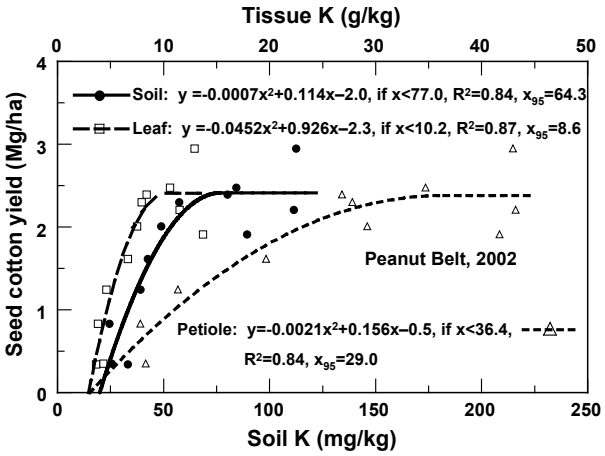

Figure 7. Yield response of cotton to soil and leaf K levels at the Peanut Belt Research Station in 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

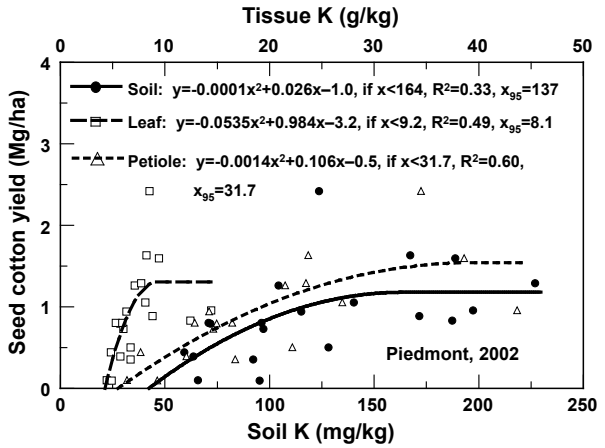

Figure 8. Yield response of cotton to soil and leaf K levels at the Piedmont Research Station in 2002. Plant tissue results are for samples collected one week after first bloom. Each data point represents a single experimental plot.

Leaf and petiole K gradient response. Yield also increased as leaf K and petiole K concentrations increased. Critical leaf K levels were identified for all sampling dates at all site-years (Table 5), and critical petiole K levels identified for most cases (Table 6). Because there were few data points in the plateau region of these relationships (Fig. 6-8), the reliability of these critical levels is less certain than for levels of leaf and petiole P.

Table 5. Regression model parameters indicating seed cotton yield (y) in response to leaf K gradients (x). Where applicable, the critical level (x_{95}) was based on the x value associated with a yield level of 95% of the projected plateau (y_o) using the quadratic-plateau method: $y = a + bx + cx^2$, if $x < x_o$ or $y = a + bx$. Otherwise, linear regression was used: $y = a + bx$, with no defined critical level.

Sampling stage [y]	Site	Year	a (Mg ha^{-1})	b [(Mg ha^{-1})(g kg^{-1})$^{-1}$]	c [(Mg ha^{-1})(g kg^{-1})$^{-2}$]	x_o (g kg^{-1})	y_o (Mg ha^{-1})	x_{95} (g kg^{-1})	R^2
-1	Peanut	2002	-5.22	1.256	-0.0519	12.1	2.37	10.6	0.86** [z]
	Piedmont	2002	-4.11	0.902	-0.0382	11.8	1.22	10.2	0.42**
+1	Peanut	1999	-2.76	0.536	-0.0165	16.2	1.60	14.0	0.95**
	Peanut	2002	-2.33	0.926	-0.0452	10.2	2.41	8.6	0.87**
	Piedmont	2002	-3.22	0.984	-0.0535	9.2	1.30	8.1	0.49**
+3	Peanut	1999	-2.92	0.891	-0.0494	9.0	1.105	8.0	0.61**
	Peanut	2002	-3.20	0.702	-0.0219	16.0	2.43	13.7	0.66**
	Piedmont	2002	-0.99	0.459	-0.0223	10.3	1.37	8.6	0.54
+5	Peanut	1999	-1.87	0.978	-0.0744	6.6	1.34	5.6	0.92**
	Peanut	2002	-2.58	1.450	-0.1134	6.4	2.05	5.4	0.35*
	Piedmont	2002	-2.73	1.245	-0.0969	6.4	1.26	5.6	0.38**

[y] Sampling stage is relative to first bloom (0).

[z] Values designated with * and ** are significantly different at $P \leq 0.05$ and 0.01, respectively.

Table 6. Regression model parameters indicating seed cotton yield (y) in response to petiole K gradients (x). Where applicable, the critical level (x_{95}) was based on the x value associated with a yield level of 95% of the projected plateau (y_o) using the quadratic-plateau method: $y = a + bx + cx^2$, if $x < x_o$ or $y = a + bx$. Otherwise, linear regression was used: $y = a + bx$, with no defined critical level.

Sampling stage [y]	Site	Year	a (Mg ha^{-1})	b [(Mg ha^{-1})(g kg^{-1})$^{-1}$]	c [Mg ha^{-1})(g kg^{-1})$^{-2}$]	x_o (g kg^{-1})	y_o (Mg ha^{-1})	x_{95} (g kg^{-1})	R^2
-1	Peanut	2002	-1.80	0.169	-0.0017	49.7	2.40	41.3	0.83** [z]
+1	Peanut	1999	-0.91	0.057	- - -	- - -	- - -	- - -	0.94**
	Peanut	2002	-0.46	0.156	-0.0021	36.4	2.38	29.0	0.84**
	Piedmont	2002	-0.54	0.106	-0.0014	39.3	1.54	31.7	0.60**
+3	Peanut	1999	-1.08	0.078	- - -	- - -	- - -	- - -	0.67**
	Piedmont	2002	-0.59	0.213	-0.0068	15.6	1.08	12.8	0.28*
+5	Peanut	1999	-0.46	0.153	-0.0034	22.16	1.23	17.9	0.77**
	Peanut	2002	-1.82	0.304	-0.0056	27.1	2.31	22.6	0.95*

[y] Sampling stage is relative to first bloom (0).

[z] Values designated with * and ** are significantly different at $P \leq 0.05$ and 0.01, respectively.

Critical K levels. The critical soil K levels at first-bloom in 2002 at the Peanut Belt site (64 mg kg^{-1}) and the Piedmont site (137 mg kg^{-1}) are within ranges previously reported in the literature (see Table 7). Estimates include lower values, 39 mg kg^{-1} using Mehlich-3 at the same Peanut Belt site (Cox and Barnes, 2002) and 40 mg kg^{-1} using Mehlich-1 (Cope, 1984), but other studies found critical levels ranging from 60 to 160 mg kg^{-1} using several different extractants.

Our results indicate that while either leaf or petiole K can be used to assess K fertility status, critical concentrations in both tissues decline during the several weeks of the flowering period, which is consistent with other reports (Ulrich and Ohki, 1966; Basset and Mackenzie, 1976; Mitchell and Baker, 2000; see Table 7). During the period 1 wk prior to first bloom until 3 wk after first bloom in this study, mean critical leaf K level declined from 10.4 g kg^{-1} to 10.1 g kg^{-1}. A more rapid decline to 5.5 g kg^{-1} oc-

curred by 5 wk after first bloom. Values obtained at the corresponding sampling times are similar to those reported by Cox and Barnes (2002) and Howard et al. (2001), but are lower than the currently used sufficiency ranges for cotton in the southeastern U.S. (Mitchell and Baker, 2000). The critical petiole K level in this study was 41.3 g kg^{-1} at 1 wk prior to first bloom (based on a single site), which declined to 20.2 g kg^{-1} at 5 wk after first bloom (Table 6). These petiole K results are similar to critical levels at corresponding sampling times for Tennessee (Howard et al., 2001) and California (Bassett and MacKenzie, 1976; Weir et al., 1996).

CONCLUSIONS

Yield increased several-fold in response to P and K fertility gradients for all site years. Additional data at higher soil test levels would more clearly demonstrate critical levels in cases with few data points beyond predicted plateau levels. Nevertheless, critical soil P and K levels in this study were similar to several published critical levels. Critical soil P levels were also similar to projections of a model derived for corn based on both soil-test P and clay content. Critical soil P and K levels in this study are higher than those reported by Cox and Barnes (2002), possibly due to under-fertilization of the previous

Table 7. Critical soil and plant tissue K levels from this study and selected publications

Parameter		This study [x]		Reference [y]	Critical level
Critical level of soil K	n	(mg kg^{-1})	CV (%)		(mg kg^{-1})
	1	Peanut Belt: 64	- - -	Ulrich & Ohki (1966)	60 to 92.5
				Cope (1984)	40
				Baker et al. (1994)	105
	1	Piedmont: 137	- - -	Davis et al. (1996)	130
				Weir et al. (1996)	105
				Howard et al. (2001)	72 to 141
				Adeli & Varco (2002)	160
				Cox & Barnes (2002)	39
Critical level of leaf K [z]		(g kg^{-1})	CV (%)		(g kg^{-1})
-1 wk	2	10.4	2.7		
wk of 1st bloom	- -	- - -	- - -	Howard et al. (2001)	11.1
+1 wk	3	10.2	32.0	Cope (1984)	9 to 15
				Mitchell & Baker (2000)	15
+3 wk	3	10.1	31.0	Cox & Barnes (2002)	9.0
+5 wk	3	5.5	2.1	Mitchell & Baker (2000)	7.5
Critical level of petiole K [z]		(g kg^{-1})	(%)		(g kg^{-1})
-1 wk	1	41.3	- - -		
wk of 1st bloom	- -	- - -		Bassett & MacKenzie (1976)	40
				Howard et al. (2001)	37
+1 wk	3	30.4	6.3	Ulrich & Ohki (1966)	45
+2 wk	- -	- - -	- - -	Weir et al. (1996)	27.0
+3 wk	1	12.8	- - -		
+4 wk	- -	- - -	- - -	Bassett & MacKenzie (1976)	30
+5 wk	2	20.2	16.4	Ulrich & Ohki (1966)	10
+6 wk	- -	- - -	- - -	Bassett & MacKenzie (1976)	15

[x] Critical level of soil K in this study was determined using the Mehlich-3 extractant.

[y] Critical levels of soil K for Ulrich and Ohki, Cope, Baker et al., Davis et al., Weir et al., Howard et al., Adeli and Varco, and Cox and Barnes were determined by various extractants not currently used by soil test laboratories, Mehlich-1, Mehlich-1, Mehlich-3, Mehlich-3, Mehlich-1, Lancaster, and Mehlich-3 extractants, respectively.

[z] Critical level of leaf K were determined by Cope and Mitchell and Baker (at +1week) at early bloom, and by Mitchell and Baker (at +5 week) at late bloom/maturity. Critical levels of petiole K were determined by Ulrich and Ohki (at +1 week) at early bloom, and by Ulrich and Ohki (at +5 week) at late bloom/maturity.

experiment. Soil data in this study indicate higher P levels may be warranted for the Tidewater soils than indicated in other studies from other environments. As reported previously, critical leaf P, leaf K, and petiole K levels were dependent upon sampling time relative to floral initiation and were reduced as the crop matured.

Variability among reports of soil critical levels is greater than among plant tissue critical levels. Note that critical soil P levels range from 6 to 40 mg kg^{-1} (6-fold) and critical soil K levels range from 39 to 160 mg kg^{-1} (4-fold). In comparison, at 1 wk after first bloom, critical leaf P levels range from 2 to 3 g kg^{-1}, critical leaf K levels range from 9 to 15 g kg^{-1}, and critical petiole K levels range from 30 to -45 (all < 2-fold). Greater variability among critical soil nutrient levels can be attributed to differences in laboratory extractants, soil composition, climate, sampling time, and perhaps crop management.

Experiments such as this reassess fertility recommendations with newer cultivars and different management practices and soil or climatic regions. The limited number of suitable sites in Cotton Belt states presents an opportunity for regional coordination for further understanding the relationship between soil fertility gradients, plant tissue concentrations, and crop yield. Preservation of these few existing sites is crucial, since fertility levels on much commercial and research station farmland has already been fertilized to levels near or above critical levels. In some cases, several years might be required for sufficient crop nutrient removal to reduce fertility levels enough to detect responses to added fertilizer (Cox et al., 1981). A more credible fertility response database should enhance acceptance of research-based recommendations, and should enhance farm profits and reduce environmental impacts of farming.

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DISCLAIMER

Mention of commercial names does not constitute endorsement of any product or imply that alternative products are less suitable.

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